Effect of Cyclic Fatigue Tests on Aging and Their Translational Implications for Survival of All-Ceramic Tooth-Borne Single Crowns and Fixed Dental Prostheses

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Abstract: PURPOSE The objective of this systematic review was to elaborate the aging effect of cyclic fatigue tests on mechanical durability of all-ceramic single crowns and fixed dental prostheses (FDP). MATERIALS AND METHODS Original scientific papers published in the MEDLINE (PubMed) database in English between 01/01/1950 and 12/31/2013 on cyclic loading on all-ceramics were included in this systematic review. The following MeSH terms, search terms, and their combinations were used: "in vitro," "stress mechanical," "crowns," "denture, partial, fixed," "dentistry," "fatigue," "all-ceramic," "zirconia," "fixed dental prosthesis," "FDP," "bridges," and "cyclic loading." Two reviewers performed screening and analyzed the data. Only the studies that reported on both static fracture strength and static fracture after fatigue of all-ceramic single crowns and FDPs that allowed comparison of aging effect through cyclic loading were included. RESULTS The selection process resulted in a final sample of 14 journal articles. In total, 9 articles were identified related to all-ceramic single crowns, 3 of which were on anterior and 6 on posterior crowns, and 5 articles on 3-unit FDPs, all of which were on posterior FDPs. Fatigue cycles varied between minimum of 1000 to maximum 1,200,000 cycles for crowns and 10,000 to 2,000,000 cycles for 3-unit FDPs. The applied force during cyclic loading varied between 20 to 300 N for single crowns and 49 to 200 N for 3-unit FDPs. For the 3-unit FDPs, fracture strength results showed slightly decreased values after cyclic loading (659 ± 182 to 2333 ± 183 N) compared to static loading only (841 ± 244 to 2434 ± 154 N). For crowns similar trends were not observed, but cyclic loading decreased the fracture strength in only some materials after cyclic loading (659 ± 182 to 2333 ± 183 N) compared to static loading only (395 ± 96 to 2726 N). CONCLUSIONS An inclination for decreased static fracture strength could be observed after cyclic loading of all-ceramic single crowns and FDPs, but this was material specific. Due to the heterogeneity of data such as aging, loading conditions, and fewer experimental groups, statistical analysis could not be performed. Cyclic loading tests require more standardized guidelines for testing and reporting.

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Effect of cyclic fatigue tests on aging and their translational implications for survival of all-ceramic tooth-borne single crowns and fixed dental prosthesis

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Short title: *Cyclic fatigue of all-ceramic restorations*

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ABSTRACT

Purpose: The objective of this systematic review was to elaborate the aging effect of cyclic fatigue tests on mechanical durability of all-ceramic single crowns and fixed-dental prosthesis (FDP).

Materials and Methods: Original scientific papers published in MEDLINE (PubMed) database in English between 01/01/1950 and 12/31/2013 on cyclic loading on all-ceramics were included in this systematic review. The following MeSH terms, search terms and their combinations were used: “in vitro”, “stress mechanical”, “crowns”, “denture, partial, fixed”, “dentistry”, “fatigue”, “all-ceramic”, “zirconia”, “fixed dental prosthesis”, “FDP”, “bridges”, “cyclic loading”. Two reviewers performed screening and analyzed the data. Only the studies that reported on both static fracture strength and static fracture after fatigue of all-ceramic single crowns and FDPs were included that allowed comparison of aging effect through cyclic loading.

Results: The selection process resulted in the final sample of 14 journal articles. In total, 9 articles were identified related to all-ceramic single crowns, 3 of which were on anterior and 6 on posterior crowns, and 5 articles on 3-unit FDPs all of which were on posterior FDPs. Fatigue cycles varied between minimum of 1000 to maximum 1.200.000 cycles for crowns and 10.000 to 2.000.000 cycles for 3-unit FDPs. The applied force during cyclic loading varied between 20 to 300 N for the 3-unit FDPs and 49 to 200 N for single crowns. For the 3-unit FDPs, fracture strength results showed slightly decreased values after cyclic loading (659±182 - 2333±183 N) compared to static loading only (841±244 - 2434±154 N). For crowns similar trend could not be observed but cyclic loading decreased the fracture strength in only some materials after cyclic loading (659±182 - 2333±183 N) compared to static loading only (395±96 - 2726 N).

Conclusion: An inclination for decreased static fracture strength could be observed after cyclic loading of all-ceramic single crowns and FDPs but this was material specific. Due to heterogeneity of data such as aging, loading conditions, and less number of experimental groups, statistics could not be performed. Cyclic loading tests require more standardized guidelines for testing and reporting.

Keywords: Aging; All-ceramic; Cyclic loading; Cyclic fatigue; Dynamic loading; Fatigue loading; Fatigue test; FDP; FPD; Fracture strength; In vitro; Load-bearing capacity; Test method; Tooth-borne fixed dental prosthesis

1. Introduction

Investigations on durability of restorations are crucial for clinical dentistry since mechanical failures in the form of fractures have financial consequences both for the patient and the dentist. Removal and repair of restorations may be arduous and have also biological costs. Since durability testing of dental restorations in clinical trials is not possible due to technical and ethical considerations, materials and techniques are often tested in vitro. The testing and evaluation of the material characteristics and durability prior to clinical use is essential to avoid both financial and biological costs.

Load to fracture test is a common way of testing dental materials used for fixed dental prosthesis (FDP) to assess their mechanical strength for different indications. Today, an increased plethora of metal, all-ceramic or polymeric materials are being offered for clinical use. Neither ethically, nor technically it is possible to test their performance in randomized controlled clinical trials. Therefore, preclinical evaluations help to rank physical and mechanical properties of materials. Ranking prosthetic materials after such tests are generally taken into consideration for clinical indications especially for posterior segments of the mouth where increased chewing forces are experienced. Static load-bearing tests require a controlled environment where the specimen dimensions and the loading conditions are standardized. Although there are norms for static testing FDP materials (DIN EN ISO 22674),[23] among in vitro tests, a great heterogeneity is being noticed in the dental literature related to load to fracture tests.[31] Moreover their clinical relevancy is being questioned since the magnitude of loading is not representative of restorations in service and does not incorporate factors related to environmental effects.[31] On the other hand, in vitro studies involving fatigue tests may have more translational meaning as they simulate the in vivo environment. This type of preclinical examination helps to rank the growing possibilities of various materials and techniques for the dental restorations for certain clinical indications that demand different physical and mechanical properties. Fatigue testing requires a controlled and standardized environment prior to investigate the cause of failure due to evaluation of different clinical indication for varying dental materials such as metal-ceramics, all-ceramics where the latter is more prone to fractures clinically.

The objective of this systematic review therefore was to elaborate the aging effect of cyclic fatigue tests on mechanical durability of all-ceramic single crowns and fixed-dental prosthesis (FDP).

2. Material and methods

2.1 Search strategy

An electronic search at MEDLINE (PubMed) (http://www.ncbi.nlm.nih.gov/pubmed/) from 01/01/1950 to 31/12/2013 was conducted for English articles. Following MeSH terms, search terms and their combinations were used for this search: “in vitro”, “stress mechanical”, “crowns”, “denture, partial, fixed”, “dentistry”, “dental implants”, “cyclic loading”, “fatigue”, “all-ceramic”, “zirconia”, “fixed dental prosthesis”, “FDP”, “bridges”. The MEDLINE search yielded 709 journal articles to be screened for possible inclusion based on titles and abstracts. A further manual search covering the period from 01/01/1981 up to and including 31/12/2013 was performed on the following journals: Journal of Dental Research, Dental Materials, International Journal of Prosthodontics, Journal of Prosthetic Dentistry, Journal of Prosthodontics, and European Journal of Prosthetic and Restorative Dentistry. In addition, hand searches were performed on bibliographies of the selected articles as well as identified narrative reviews to find out whether the search process has missed any relevant article. This did not add to additional articles to be involved in the review process.

2.2 Inclusion/Exclusion criteria

Journal articles in English concerning in vitro studies of all-ceramic restorations reporting on fracture strength before and after cyclic fatigue tests were included. Articles were not included if results were not presented in Newtons (N), specimens were not loaded vertically, studies included implants or posts or articles with in vitro tests of inlays or overlays. This review focused on bilayered ceramic materials, therefore monolithic restorations have been excluded. Also, cantilever FDPs and extension units were not involved in the revision.

2.3 *Selection of studies*

The search process led to titles of 709 journal articles that were reviewed by two independent reviewers (M.J. and M.Ö.), for possible inclusion in this systematic review. After title screening, 237 abstracts were selected. From abstract evaluation, 109 were considered relevant and full text articles were downloaded. Thereafter, from 109 journal articles, 14 were them were included in this review. Process of identifying the studies included in the review is presented in Fig. 1.

2.4 Data extraction

The data collection form containing 40 items was created and used to evaluate the experimental environment of the in vitro studies described in the 14 relevant articles concerning cyclic fatigue tests. Disagreement regarding data extraction was resolved by discussion and a consensus was reached. The variables were recorded and tabulated in Excel sheets. The variables that could not be extracted or calculated were scored as 'not reported'.

2.5 Statistical analysis

Statistical analyses were performed using the Statistical Package for the Social Sciences (version 18.0, SPSS Inc, Chicago, IL, USA). Abstracts of the full articles were used for the inter-observer agreement expressed as weighted Cohen's kappa. For descriptive statistics means and standard deviations, or medians and interquartile ranges in skewed distributions were noted. At least 6 experimental groups with identical test parameters were needed to run statistical analysis. Due to heterogeneity of information or insufficient number of experimental groups, data could not be analyzed even using Stängel-Blatt-Diagramme.

3. Results

The Kappa score for agreement between the reviewers after screening the abstracts was 0.85. The selection process resulted in the final sample of 14 journal articles.[5,11,16,18,24,33,34,36,55-58,66,67] In total, 9 articles were identified related to all-ceramic single crowns, 3 of which were on anterior and 6 on posterior crowns, and 5 articles on 3-unit FDPs all of which were on posterior FDPs. In the selected 14 articles, a total of 43 experimental subgroups were identified where fracture strength results were reported in N. After data analysis, 50 articles were excluded and the main reasons were due to lack of initial fracture load,[1,2,3,8,10,12,13,15,26,29,30,32,35,37,41-43,45-47,49-53] final fracture load,[2,6,9,10,14,15,19,20,25,27,29,30,39,40,47,54,48,60-63,71] initial and final fracture load (only fatigue survival),[2,10,15,29,30,47,54,58] different units such as N and kg in one study,[1,2,9,12] step-stress loading without initial loading data,[14,27,61,63,64] not-anatomic crowns[22] and the use of monolithic restorations only.[4,17,29,72] (Supplement 1).[1-4,6,8-10,12-15,17,19,20,22,25-27,29,30,32,35,37,39,40-43,45-47,49-54,58,60-65,68-72]

Fatigue cycles varied between minimum of 1000 to maximum 1.200.000 cycles for crowns and 10.000 to 2.000.000 cycles for 3-unit FDPs (Tables 1a-b). The applied force during cyclic loading varied between 0 to 300 N for the 3-unit FDPs and 49 to 200 N for crowns showing great deviation between or within studies. Furthermore, loading was performed with stainless steel indenters having diameters from 6 mm to 10 mm. Similarly, for the test of the crowns, loading indenters ranged from 1.3 mm to 4 mm showing a huge deviation. Load magnitude ranged between 0 to 300 N during cyclic loading.

There were altogether 5 studies selected for the 3-unit FDPs. Such studies are usually costly and the number of these studies was less than those of studies on crowns (n=9). The number of experimental groups for the FDPs was 10, and the materials ranged from zirconia (n=5) to sintered alumina (n=2) or lithium disilicate ceramic (n=3). The temperature of the fatigue chambers ranged between 5 and 65°C.

For the 3-unit FDPs, fracture strength results showed slightly decreased values after cyclic loading (659±182 - 2333±183 N) compared to static loading only (841±244 - 2434±154 N). For crowns similar trend could not be observed but cyclic loading decreased the fracture strength in only some materials after cyclic loading (659±182 - 2333±183 N) compared to static loading only (395±96 - 2726 N).

4. Discussion

Cyclic fatigue loading test intend to investigate the mechanical durability of dental reconstruction materials prior to clinical trials in order to avoid costly interventions upon failures. One of the main causes of structural failure in restorative dentistry is fatigue. Although static fracture tests may help to screen the durability of FDPs, cyclic loading could be considered a more clinically relevant testing approach. It has been reported that dental restorations fail more frequently under cyclic loading tests that are well below the ultimate flexural strength of these materials as opposed to the application of a single, relatively higher static load.[7] This systematic review therefore investigated the aging effect of cyclic fatigue tests on mechanical durability of all-ceramic single crowns and FDPs.

One major problem during the search process was the lack of MeSH terms related to cyclic loading or other fatigue related terms. In the dental literature a great number of different terms are being used in order to describe some mechanical aging procedures for reconstructive materials. This issue needs to be solved primarily so that future studies could report on identical search terms. Furthermore, in order to investigate the aging effect of cyclic loading on the durability on FDP materials, the materials should be tested with and without exposure to cyclic loading. Unfortunately, the main reason for exclusion was because the effect of aging could not be identified since no control groups were available presenting the initial fracture load values without fatigue conditions. Focusing only on the final fracture strength after cyclic fatigue loading would not allow for identifying the aging effect of cyclic loading.[1,2,3,8,10,12,13,15,26,29,30,32,35,37,41-43,45-47,49-53]

The parameters employed by the investigators such as the number of fatigue cycles, loading jigs, frequency of loading, presence of humid environment, involvement of hydrothermal aging conditions showed a great variation in the current dental literature. Furthermore, loading was performed with stainless steel indenters having diameters ranging from 6 to 10 mm and in some articles, the diameter of the loading jig or indenter was not enclosed.[2,6,9,10,13,15,25,29,35,53,54,59] In fact, cone crack or Herzian crack formation is highly dependent on the diameter and sharpness of the indenter.[38] Thus, the type and size of the indenter could offset the real aging effect after cyclic loading. In addition, load magnitude ranged between 0 to 300 N during cyclic loading. The impact of high loading forces could influence the results and decrease the fatigue resistance. At least in all fatigue studies, the temperature of the fatigue chambers ranged between 5 and 65°C which was probably the only parameter kept similar between the studies. Thus, temperature and medium related corrosion process could be considered similar between the selected articles.

Nevertheless, the ultimate goal in measuring load-bearing capacity of materials is to know clinically whether they could endure chewing forces. Different testing methods and the difficulty in measuring masticatory forces result in a wide range of force values. Stress applied during mastication may range between 441 N and 981 N, 245 N and 491 N, 147 N and 368 N, and 98 N and 270 N in the molar, premolar, canine, and incisor regions, respectively.[7] A restoration should be able to withstand stress to approximately 500 N in the premolar region and 500 N to 900 N in the molar region. The results of this study indicated values higher than 659 N[11] for 3-unit FDPs after aging. Similarly for the crowns, the lowest value was 437 N for feldspathic ceramic[57] and >600 N[33,56] for high strength ceramics after 1.200.000 cycles. Certainly, glassy matrix ceramics and in this case feldspathic ceramic that presented 437 N are not indicated for posterior crowns but for comparison, the authors involved this material in the experimental design. Based on the high results above the estimated chewing forces, current all-ceramic systems could be designated as favourable materials for posterior indications.

It has to be noted that the numbers of cycles varied significantly between studies, namely ranging between minimum 1000[66] cycles to maximum 2.000.000 cycles.[11] In fact static loading after limited number of cyclic loading alone could not single out the real effect of aging procedures.

The studies on in vitro FDP systems in the dental literature practiced cycling times ranging from minimum 100[x] to maximum $28x10^6$.[48] It has been previously reported that $2x10^6$ cycles correspond to approximately four years of normal occlusal and masticatory activity.[7] The load applied also showed variations between 0 to 300 N in the included articles.[48-54] On the other hand, from the technical point of view, the magnitude of the applied load with regard to the highest-level force in a fatigue test, should not exceed 50% of the ultimate strength of the material on trial.[x] Unfortunately, ultimate stress information was often not available in the selected articles that performed static loading after fatigue. Therefore, future studies should incorporate the fatigue component in the study set-up in order to deduce more clinically relevant information considering the ultimate strength of the material to be tested after fatigue.

In limited number of articles, step-stress fatigue approach was practiced where cyclic load was applied in such a manner that 3 profiles of loading from mild to aggressive was applied on the single crowns from 100 N to 750 N with the mission of completion of 100.000 to 170.000 cycles[14,27,61,63,64] The load indenter moved sliding from lingual down to buccal being different than in other studies where loading was performed vertically, approaching the occlusal surface. In fact, such an aging method would deliver important information if the results were complete with both initial and final fracture values. At this moment, standards are lacking as regards to dynamics fatigue tests for single crowns and FDP materials. In this regard, ISO 14801[28] assigned for dynamic fatigue test for endosseous dental implants could be implemented in testing fatigue properties of FDPs, providing that implant-borne single crowns are loaded in this norm under an angle of 30±2° at >2 Hz for $5x10^6$ cycles. The clinical relevancy of such testing standards have also not been verified yet.[27] Nevertheless, such a standard method in tooth-borne FDPs would at least help for ranking mechanical durability of FDPs materials.

In this systematic review only bilayered ceramic systems were investigated. In some articles after fatigue even increased strength values were reported.[11,58] One important aspect here is that the results after the fracture of the veneering ceramic was not differentiated from the overall fracture strength. Thus, it was not possible to identify whether the loading process was continued until the framework material was fractured. If this is the case and we assume that the reported value does not belong to the principle force to fracture the veneering ceramic in the bilayered assembly. In fact, failure type analysis could have identified where whether the magnitude of force belongs to the veneering material or the core. In a previous study, the changes in energy levels revealed small failures occurring between 300 N to 500 N and continuing until final failure occurred.[44] Future studies should identify and report failures in a more systematic way perhaps also using acoustic emission (AE) signals from the material.[44]

There are several other parameters that could have played further role in fatigue resistance of FDPs such as periodontal ligament, abutment material and the cement. These parameters were not taken into consideration in this review as the principle parameters already showed much heterogeneity. Whether such parameters affect the fatigue resistance of the all-ceramics for crown and FDPs needs further focus in future studies.

Clinically sufficient fracture strength values are not known for durable FDPs. The great variation in testing parameters and testing environment would continue to create the confusion in the dental literature. Since in the future, new studies are expected to appear in this field, the following items should be disclosed in in vitro studies:

- The dimensions of the single crown or FDP, abutment type, abutment material, cement type and its chemical composition, loading conditions (jig dimensions, type, cross-head speed, indenter type, diameter), cyclic loading conditions (medium, temperature, loading magnitude, speed, number of cycles) should be defined precisely.
- The fracture strength data should be presented with confidence intervals, mean, minimum and maximum values with and without cyclic loading together with initial and maximum fracture strength values.
- At least 6 specimens should be tested in one experimental group.
- Failure types after fracture test should be listed in detail and preferably fractography should be performed.

5. Conclusion

From this study, the following could be concluded:

1. Current studies regarding the fatigue strength of single crowns and FDPs made of all-ceramic materials should be evaluated cautiously considering testing conditions. Some more systematic approach especially regarding the testing and reporting fatigue and loading conditions is needed when studying fatigue strength of such reconstructions.
2. Cyclic fatigue tests showed tendencies for decreased results for all-ceramic single crowns and 3-unit FDPs but the effect generally varied depending on the material type and the number of cycles and loading conditions. Yet, the results were often higher than generally accepted chewing forces for the posterior region.

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Captions to figures and tables:

Figures:

Fig. 1 Process of identifying the studies included in the review.

Tables:

Tables 1a-b. Fracture strength of **a)** crowns, **b)** 3-unit FDPs made of different all-ceramic materials with and without cyclic loading together with cyclic loading test parameters.

Figures:

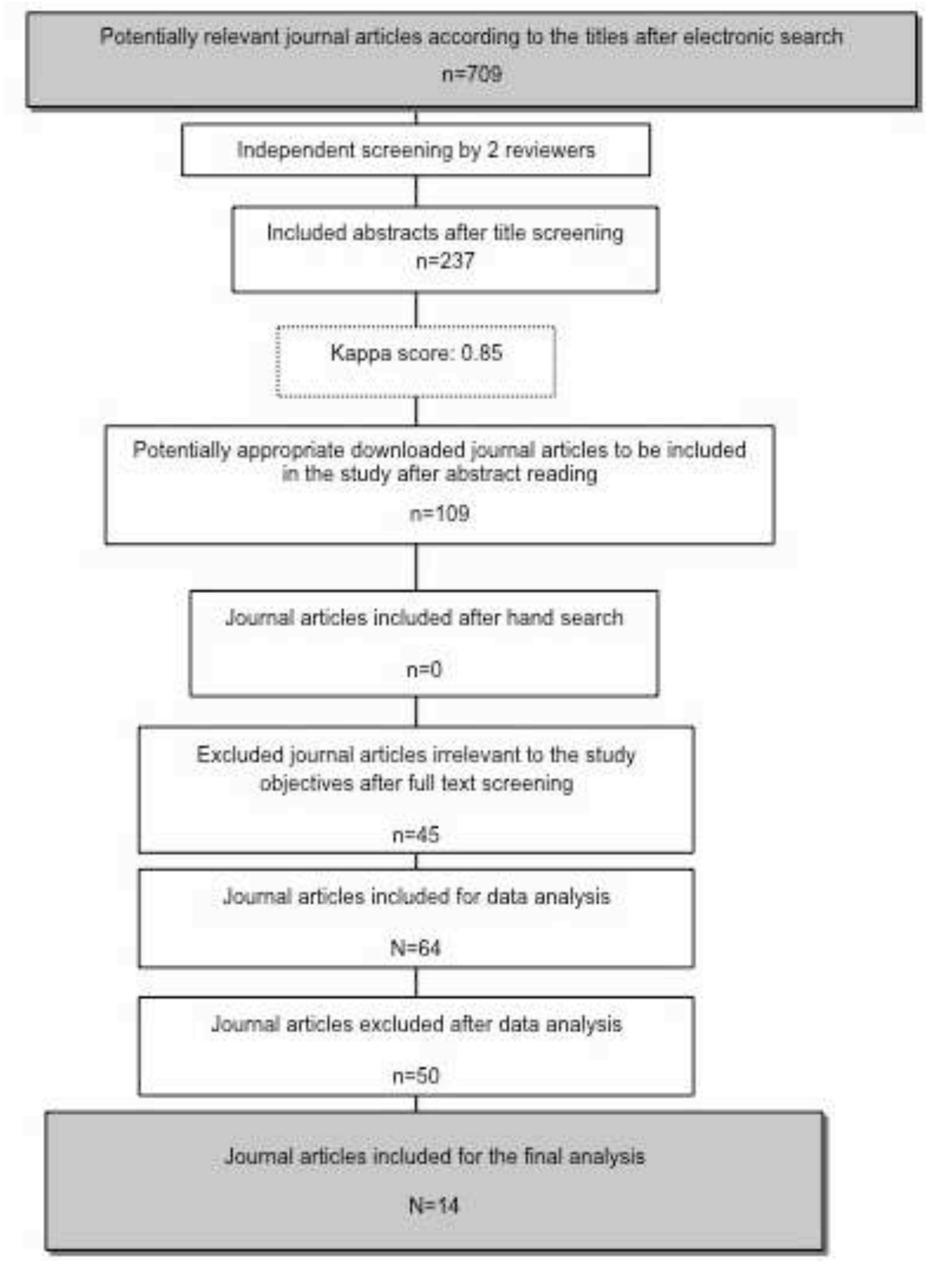

Fig. 1 Process of identifying the studies included in the review.

Tables:

Author	Framework ceramic	Veneering ceramic	Location	Fracture strength (N) before fatigue	Fatigue conditions				Fracture strength (N) after fatigue	
					Number of Cycles	Force (N)	Temperature	Indenter		Indenter
Schmitter M et al.[56]	Zirconia (Sirona in Coris UI, mono L F1)	Lithiumdisilicate ceramic (IPS e.max CAD, Crystall/Connect)	posterior	F1d= 1253±400 Fu1565±137	$1.2x10^6$	max 108	6.5-60	6 mm steel sphere	F1d= 1234±512 Fu= 1642±420	6 mm steel sphere
	Zirconia (Sirona in Coris UI, mono L F1)	Conventional veneering porcelain	posterior	F1d= 503±217 Fu= 1166±189	$1.2x10^6$	max 108	6.5-60	6 mm steel sphere	F1d= 934 Fu= 934	6 mm steel sphere
Sobrinho LC et al.[67]	(IPS Empress)		posterior	1256±84	10.000	20-300	n.a.	n.a.	1156±87	4 mm steel ball
	(IPS Empress)		posterior	1256±$84	10.000	20-300	n.a.	n.a.	1075±136	4 mm steel ball
	(OPC Jeneric Pentron)		posterior	997±200	10.000	20-300	n.a.	n.a.	924±151	4 mm steel ball
	(OPC Jeneric Pentron)		posterior	997±200	10.000	20-300	n.a.	n.a.	843±149	4 mm steel ball
	In-Ceram	Porcelain (Vita Alpha, Dentine porcelain)	posterior	817±96	10.000	20-300	n.a.	n.a.	756±169	4 mm steel ball
	In-Ceram	Porcelain (Vita Alpha, Dentine porcelain)	posterior	817±96	10.000	20-300	n.a.	n.a.	663±114	4mm steel ball
Rues S et al.[55]	Zirconia (Ceron Base DeguDent, Hanau, Germany	(Ceron Ceram Kiss)	anterior	F1d= 314±167 Fu=481±178	$1.2x10^6$	86	6.5-65	3 mm steel ball	F1d= 142±94 Fu= 153±97	1.6 mm steel ball
	Zirconia (Ceron Base	(Ceron Ceram Love)	anterior	F1d= 314±167 Fu= 481±178	$1.2x10^6$	86	6.5-65	3 mm steel ball	F1d= 255±228	1.6 mm steel ball

	DeguDent, Hanau, Germany								Fu= 258±228	
	Zirconia (Ceron Base DeguDent, Hanau, Germany	(Ceron Ceram Kiss)	anterior	F1d= 410±212 Fu= 641±155	$1.2x10^6$	86	6.5-65	3 mm steel ball	F1d= 218±94 Fu= 263±126	1.6 mm steel ball
	Zirconia (Ceron Base DeguDent, Hanau, Germany	(Ceron Ceram Love)	anterior	F1d= 410±212 Fu= 641±155	$1.2x10^6$	86	6.5-65	3 mm steel ball	F1d= 315±260 Fu= 331±279	1.6 mm steel ball
Kim JH et al.[33]	Zirconia (Ceron Base Dentsply Prosthetics)	Ceramic (IPS e.max Ceram, Ivoclar Vivadent, Schaan, Liechtenstein)	anterior	2126.9±576.9	6.000	0-200	n.a.	15 mm stainsless steel cylinder	1366.1±519.1	3 mm stainless steel hemiphere
	Zirconia (Ceron Base Dentsply Prosthetics)	Ceramic (IPS e.max Ceram, Ivoclar Vivadent)	anterior	2329.1±948.3	6.000	0-200	n.a.	15 mm stainsless steel cylinder	1232.82±403.8	3 mm stainless steel hemiphere
Borges GA et al.[16]	(InCeram Alumina, Vita Zahnfabrik)	Porcelain (Vitadur Alpha Porcelain, Vivadent, Germany)	anterior	1528±238	6.000	20-300	n.a.	n.a.	1111±198	4 mm stainless steel ball
	(InCeram Alumina, Vita Zahnfabrik)	Porcelain (Vitadur Alpha Porcelain)	anterior	1528±238	6.000	20-300	n.a.	n.a.	843±80	4 mm stainless steel ball
	(IPS Empress 2, Ivoclar)	Porcelain (D'Sign, Ivoclar)	anterior	1412±153	6.000	20-300	n.a.	n.a.	1071±75	4 mm stainless steel ball
	(IPS Empress 2, Ivoclar)	Porcelain (D'Sign, Ivoclar)	anterior	1412±153	6.000	20-300	n.a.	n.a.	895±56	4 mm stainless steel ball

	Cergogold	Porcelain (Duceragold, Degussa Dental)	anterior	947±144	60.000	20-300	n.a.	n.a.	698±201	4 mm stainless steel ball
	Cergogold	Porcelain (Duceragold)	anterior	947±144	60.000	20-300	n.a.	n.a.	585±200	4 mm stainless steel ball
	(InCeram Alumina, Vita Zahnfabrik)	Porcelain (Vitadur Alpha Porcelain, Vivadent, Germany)	anterior	1182±203	60.000	20-300	n.a.	n.a.	926±127	4 mm stainless steel ball
	(InCeram Alumina, Vita Zahnfabrik)	Porcelain (Vitadur Alpha Porcelain)	anterior	1182±203	60.000	20-300	n.a.	n.a.	710±122	4 mm stainless steel ball
	(IPS Empress 2, Ivoclar)	Porcelain (D'Sign, Ivoclar)	anterior	1154±233	60.000	20-300	n.a.	n.a.	868±67	4 mm stainless steel ball
	(IPS Empress 2, Ivoclar)	Porcelain (D'Sign, Ivoclar)	anterior	1154±233	60.000	20-300	n.a.	n.a.	760±70	4 mm stainless steel ball
	Cergogold	Porcelain (Duceragold, Degussa Dental)	anterior	646±108	60.000	20-300	n.a.	n.a.	569±209	4 mm stainless steel ball
	Cergogold	Porcelain (Duceragold)	anterior	646±108	60.000	20-300	n.a.	n.a.	512±176	4 mm stainless steel ball
Schmitter M et al.[57]	zirconia (mono L F1, Sirona in Coris Zi, Cerec Bloc, Sirona, Bensheim, Germany	Feldspathic ceramic (Ceramic Bloc)	posterior	395±96	$1.2x10^6$	max 108	6.5-60°C	6 mm steel sphere	437±35	6 mm steel sphere

	zirconia (mono L F1, Sirona in Coris Zi, Cerec Bloc, Sirona, Bensheim, Germany	Conventional veneering porcelain	posterior	1166±189	$1.2x10^6$	max 108	6.5-60°C	6 mm steel sphere	934	6 mm steel sphere
Attia A. and Kern M.[5]	Lithium disilicate galss ceramic (IPS Empress 2, Ivoclar)		posterior	1007.6±252.8	6.000	49	4-58°C	4 mm ceramic ball	861.5±140.7	4 mm stainless steel ball
	Lithium disilicate galss ceramic (IPS Empress 2, Ivoclar)		posterior	914.6±207.3	6.000	49	4-58°C	4 mm ceramic ball	786±161.6	4 mm stainless steel ball
	Lithium disilicate galss ceramic (IPS Empress 2, Ivoclar)		posterior	928±210.4	6.000	49	4-58°C	4 mm ceramic ball	641.2±179.2	4 mm stainless steel ball
Komine F. et al.[36]	Glass infiltrated aluminium oxide (In Ceram Alumina, vita Zahnfabrik)	Feldspathic ceramic (Vita VM7, Vita Zahnfabrik)	posterior	2726	$1.2x10^6$	49	5-55°C	6 mm ceramic ball	2673	n.a.
	Glass infiltrated aluminium oxide (In Ceram Alumina, vita Zahnfabrik)	Feldspathic ceramic (Vita VM7, Vita Zahnfabrik)	posterior	2520	$1.2x10^6$	49	5-55°C	6 mm ceramic ball	2083	n.a.

	Glass infiltrated aluminium oxide (In Ceram Alumina, vita Zahnfabrik)	Feldspathic ceramic (Vita VM7, Vita Zahnfabrik)	posterior	2036	$1.2x10^6$	49	5-55°C	6 mm ceramic ball	2369	n.a.
	Lithium disilicate glass ceramic (IPS e.max Press, Ivoclar, Vivadent)	(IPS e.max Press, Ivoclar, Vivadent)	posterior	1442.77±327.49	$1.2x10^6$	98	5-55°C	6 mm ceramic ball	1464.23±4 18.84	6 mm ceramic ball
Sobrinho LC et al.[66]	In-Ceram	Porcelain (Vita Alpha, Dentine porcelain)	posterior	1901±303	1.000	20-300	n.a.	n.a.	1601±198	4 mm stainless steel ball
	In-Ceram	Porcelain (Vita Alpha, Dentine porcelain)	posterior	1901±303	1.000	20-300	n.a.	n.a.	1422±112	4 mm stainless steel ball
	IPS		posterior	1751±194	1.000	20-300	n.a.	n.a.	1586±116	4 mm stainless steel ball
	IPS		posterior	1751±194	1.000	20-300	n.a.	n.a.	1467±162	4 mm stainless steel ball
	OPC		posterior	1583±115	1.000	20-300	n.a.	n.a.	1374±201	4 mm stainless steel ball
	OPC		posterior	1583±115	1.000	20-300	n.a.	n.a.	1285±200	4 mm stainless steel ball

Table 1a. Fracture strength of crowns made of different all-ceramic materials with and without cyclic loading together with cyclic loading test parameters.

Author	Framework ceramic	Veneering ceramic	Location	Fracture strength (N) before fatigue	Fatigue conditions				Fracture strength (N) after fatigue	
					Number of Cycles	Force (N)	Temperature	Indenter		Indenter
Eroğlu Z and Gurbulak AG.[24]	Zirconia (Copran zircon blanks; White Peaks Dental Systems GmbH & Co, Essen, Germany	Ceramics	posterior	2434±154.34	0.1	50	5-55°C	n.a.	2333.1±183.02	3 mm steel ball
Chitmongkolsuk S et al.[18]	IPS Empress 2, Ivoclar)	Porcelain (IPS Empress 2, Ivoclar)	posterior	1300	1.2×10^6	49	5-55°C	6mm ceramic ball	923.8	n.a.
	IPS Empress 2, Ivoclar)	Porcelain (IPS Empress 2, Ivoclar)	posterior	1273	1.2×10^6	49	5-55°C	6mm ceramic ball	1161	n.a.
Kohorst P et al.[32]	Zirconia dioxide (Cercon base, DeguDent, Hanau, Germany)		posterior	1525±76.5	1×10^6	max 100	5-55°C	n.a.	903.7±40.8	6 mm WC ball
	Zirconia dioxide (Cercon base, DeguDent, Hanau, Germany)		posterior	1525±76.5	2×10^6	max 100	5-55°C	n.a.	923.5±40.3	6 mm WC ball

	Zirconia dioxide (Cercon base, DeguDent, Hanau, Germany)		posterior	1525±76.5	$1x10^6$	max 200	5-55°C	n.a.	952.4±51.4	6mm WC ball
Beuer F et al.[11]	Sintered alumina (InCeram Alumina)	Porcelain (VM7 Vita)	posterior	851+-331	$1.2x10^6$	50	5-55°C	6mm WC ball	659±182	10 mm WC ball
	Sintered alumina reinforced with zirconia (InCeram Zirconia)	Porcelain (VM7 Vita)	posterior	841+-244	$1.2x10^6$	50	5-55°C	6mm WC ball	770±186	10 mm WC ball
	Semi sintered zirconia (InCeram YZ)	Porcelain (VM7 Vita)	posterior	981+-266	$1.2x10^6$	50	5-55°C	6mm WC ball	1042±195	10 mm WC ball
Schultheis S et al.[58]	IPS e.max CAD, Ivoclar, Vivadent, Schaan, Liechtenstein	IPS e.max Ceram (Ivoclar, Vivadent)	posterior	1298	$1.2x10^6$	49	5-55°C	3mm ceramic ball	1900	3.18 mm steel ball

Table 1b. Fracture strength of 3-unit FDPs made of different all-ceramic materials with and without cyclic loading together with cyclic loading test parameters.

	Author	Title	Publication	Exclusion Criteria
1	Aboushelib MN.[1]	Fatigue and fracture resistance of zirconia crowns prepared with different finish line designs.	J Prosthodont 2012;21:22-27.	No initial fracture load, force presented in kg, indender-shape not defined. Surface area is missing.
2	Aboushelib MN.[2]	Simulation of cumulative damage associated with long term cyclic loading using a multi-level strain accommodating loading protocol.	Dent Mater 2013;29:252-258.	No initial and final fracture load, force presented in N and kg.
3	Alhasanyah A, Vaidyanathan TK, Flinton RJ.[3]	Effect of core thickness differences on post-fatigue indentation fracture resistance of veneered zirconia crowns.	J Prosthodont 2013;22:383-390.	No initial fracture load.
4	Attia A, Abdelaziz KM, Freitag S, Kern M.[4]	Fracture load of composite resin and feldspathic all-ceramic CAD/CAM crowns.	J Prosthet Dent 2006;95:117-123.	Monolithic restorations.
5	Azer SS, Drummond JL, Campbell SD, El Moneim Zaki A.[6]	Influence of core buildup material on the fatigue strength of an all-ceramic crown.	J Prosthet Dent 2001;86:624-631.	No final fracture load.
6	Behr M, Rosentritt M, Mangelkramer M, Handel G.[8]	The influence of different cements on the fracture resistance and marginal adaptation of all-ceramic and fiber-reinforced crowns.	Int J Prosthodont 2003;16:538-542.	No initial fracture load.
7	Belli R, Frankenberger R, Appelt A, Schmitt J, Baratieri LN, Greil P, Lohbauer U.[9]	Thermal-induced residual stresses affect the lifetime of zirconia-veneer crowns.	Dent Mater 2013;29:181-190.	No final fracture load.
8	Belli R, Petschelt A,	Thermal-induced residual stresses affect the fractographic	J Mech Behav Biomed Mater	No final and initial fracture load.

	Lohbauer U.[10]	patterns of zirconia-veneer dental prostheses.	2013;21:167-177.	
9	Beuer F, Stimmelmayr M, Gueth JF, Edelhoff D, Naumann M.[12]	In vitro performance of full-contour zirconia single crowns.	Dent Mater 2012;28:449-456.	No initial fracture load.
10	Blatz MB, Oppes S, Chiche G, Holst S, Sadan A.[13]	Influence of cementation technique on fracture strength and leakage of alumina all-ceramic crowns after cyclic loading.	Quintessence Int 2008;39:23-32.	No initial fracture load.
11	Bonfante EA, Rafferty B, Zavanelli RA, Silva NR, Rekow ED, Thompson VP, Coelho PG.[14]	Thermal/mechanical simulation and laboratory fatigue testing of an alternative yttria tetragonal zirconia polycrystal core-veneer all-ceramic layered crown design.	Eur J Oral Sci 2010;118:202-209.	No final fracture load.
12	Bonfante EA, Sailer I, Silva NR, Thompson VP, Dianne Rekow E, Coelho PG.[15]	Failure modes of Y-TZP crowns at different cusp inclines.	J Dent 2010;38:707-712.	No initial and final fracture load.
13	Chen HY, Hickel R, Setcos JC, Kunzelmann KH.[17]	Effects of surface finish and fatigue testing on the fracture strength of CAD-CAM and pressed-ceramic crowns.	J Prosthet Dent 1999;82:468-475.	Monolithic restorations.
14	Coelho PG, Bonfante EA, Silva NR, Rekow ED, Thompson VP.[19]	Laboratory simulation of Y-TZP all-ceramic crown clinical failures.	J Dent Res 2009;88:382-386.	No final fracture load.

15	Coelho PG, Silva NR, Bonfante EA, Guess PC, Rekow ED, Thompson VP.[20]	Fatigue testing of two porcelain-zirconia all-ceramic crown systems.	Dent Mater 2009;25:1122-1127.	No final fracture load.
16	Corazza PH, Feitosa SA, Borges AL, Della Bona A.[22]	Influence of convergence angle of tooth preparation on the fracture resistance of Y-TZP-based all-ceramic restorations.	Dent Mater 2013;29:339-347.	Restorations not anatomic.
17	Gresnigt MM, Ozcan M, Kalk W, Galhano G.[25]	Effect of static and cyclic loading on ceramic laminate veneers adhered to teeth with and without aged composite restorations.	J Adhes Dent 2011;13:569-577.	No final fracture load.
18	Guess PC, Bonfante EA, Silva NR, Coelho PG, Thompson VP.[26]	Effect of core design and veneering technique on damage and reliability of Y-TZP-supported crowns.	Dent Mater 2013;29:307-316.	No final fracture load.
19	Guess PC, Zavanelli RA, Silva NR, Bonfante EA, Coelho PG, Thompson VP.[27]	Monolithic CAD/CAM lithium disilicate versus veneered Y-TZP crowns: comparison of failure modes and reliability after fatigue.	Int J Prosthodont. 2010;23:434-442.	No final fracture load. (
20	Kassem AS, Atta O, El-Mowafy O.[29]	Combined effects of thermocycling and load-cycling on microleakage of computer-aided design/computer-assisted manufacture molar crowns.	Int J Prosthodont 2011;24:376-378.	Monolithic restoration only. No initial and final fracture load.
21	Kassem AS, Atta O, El-Mowafy O.[30]	Fatigue resistance and microleakage of CAD/CAM ceramic and composite molar	J Prosthodont 2012;21:28-32.	No initial and final fracture load.

		crowns.		
22	Kheradmandan S, Koutayas SO, Bernhard M, Strub JR.[32]	Fracture strength of four different types of anterior 3-unit bridges after thermo-mechanical fatigue in the dual-axis chewing simulator.	J Oral Rehabil 2001;28:361-369.	No initial fracture load.
23	Kolbeck C, Rosentritt M, Handel G.[35]	Fracture strength of artificially aged 3-unit adhesive fixed partial dentures made of fiber-reinforced composites and ceramics: an in vitro study.	Quintessence Int 2006;37:731-735.	No initial fracture load.
24	Larsson C, Holm L, Lovgren N, Kokubo Y, Vult von Steyern P.[37]	Fracture strength of four-unit Y-TZP FPD cores designed with varying connector diameter. An in-vitro study.	J Oral Rehabil 2007;34:702-709.	No initial fracture load.
25	Lorenzoni FC, Martins LM, Silva NR, Coelho PG, Guess PC, Bonfante EA, Thompson VP, Bonfante G.[39]	Fatigue life and failure modes of crowns systems with a modified framework design.	J Dent 2010;38:626-634.	No final fracture load.
26	Mörmann W, Wolf D, Ender A, Bindl A, Göhring T, Attin T.[40]	Effect of two self-adhesive cements on marginal adaptation and strength of esthetic ceramic CAD/CAM molar crowns.	J Prosthodont 2009;18:403-410.	No final fracture load.
27	Mahmood DJ, Linderoth EH, Vult Von Steyern P.[41]	The influence of support properties and complexity on fracture strength and fracture mode of all-ceramic fixed dental prostheses.	Acta Odontol Scand 2011;69:229-237.	No initial fracture load.

28	Ohlmann B, Dittmar A, Rues S, Rammelsberg P.[42]	Comparison of fracture-load values of cantilevered FDPs.	Acta Odontol Scand 2013;71:584-589.	No initial fracture load.
29	Okutan M, Heydecke G, Butz F, Strub JR.[43]	Fracture load and marginal fit of shrinkage-free ZrSiO4 all-ceramic crowns after chewing simulation.	J Oral Rehabil 2006;33:827-832.	No initial fracture load.
30	Preis V, Behr M, Hahnel S, Handel G, Rosentritt M.[45]	In vitro failure and fracture resistance of veneered and full-contour zirconia restorations.	J Dent 2012;40:921-928.	No initial fracture load.
31	Preis V, Letsch C, Handel G, Behr M, Schneider-Feyrer S, Rosentritt M.[46]	Influence of substructure design, veneer application technique, and firing regime on the in vitro performance of molar zirconia crowns.	Dent Mater 2013;29:e113-21.	No initial fracture load.
32	Rekow ED, Zhang G, Thompson V, Kim JW, Coehlo P, Zhang Y.[47]	Effects of geometry on fracture initiation and propagation in all-ceramic crowns.	J Biomed Mater Res B Appl Biomater 2009;88:436-446.	No initial and final fracture load.
33	Rosentritt M, Behr M, Gebhard R, Handel G.[49]	Influence of stress simulation parameters on the fracture strength of all-ceramic fixed-partial dentures.	Dent Mater 2006;22:176-182.	No initial fracture load.
34	Rosentritt M, Behr M, Scharnagl P, Handel G, Kolbeck C.[50]	Influence of resilient support of abutment teeth on fracture resistance of all-ceramic fixed partial dentures: an in vitro study.	Int J Prosthodont 2011;24:465-468.	No initial fracture load.
	Rosentritt M, Kolbeck C,	Influence of the fabrication process on the in vitro	Clin Oral Investig 2011;15:1007-	No initial fracture load.

35	Handel G, Schneider-Feyrer S, Behr M.[51]	performance of fixed dental prostheses with zirconia substructures.	1012.	
36	Rosentritt M, Plein T, Kolbeck C, Behr M, Handel G.[52]	In vitro fracture force and marginal adaptation of ceramic crowns fixed on natural and artificial teeth.	Int J Prosthodont 2000;13:387-391.	No initial fracture load.
37	Rosentritt M, Siavikis G, Behr M, Kolbeck C, Handel G.[53]	Approach for valuating the significance of laboratory simulation.	J Dent 2008;36:1048-1053.	No initial fracture load.
38	Rosentritt M, Steiger D, Behr M, Handel G, Kolbeck C.[54]	Influence of substructure design and spacer settings on the in vitro performance of molar zirconia crowns.	J Dent 2009;37:978-983.	No initial and final fracture load.
39	Senyilmaz DP, Canay S, Heydecke G, Strub JR.[58]	Influence of thermomechanical fatigue loading on the fracture resistance of all-ceramic posterior crowns.	Eur J Prosthodont Restor Dent 2010;18:50-54.	No initial and final fracture load.
40	Silva NR, Bonfante E, Rafferty BT, Zavanelli RA, Martins LL, Rekow ED, Thompson VP, Coehlo PG.[60]	Conventional and modified veneered zirconia vs. metalloceramic: fatigue and finite element analysis.	J Prosthodont 2012;21:433-439.	No final fracture load.
41	Silva NR, Bonfante EA, Rafferty BT, Zavanelli RA, Rekow ED, Thompson VP,	Modified Y-TZP core design improves all-ceramic crown reliability.	J Dent Res 2011;90:104-108.	No final fracture load.

	Coelho PG.[61]			
42	Silva NR, Bonfante EA, Zavanelli RA, Thompson VP, Ferencz JL, Coelho PG.[62]	Reliability of metalloceramic and zirconia-based ceramic crowns.	J Dent Res 2010;89:1051-1056.	No final fracture load.
43	Silva NR, Thompson VP, Valverde GB, Coelho PG, Powers JM, Farah JW, Esquivel-Upshaw J.[63]	Comparative reliability analyses of zirconium oxide and lithium disilicate restorations in vitro and in vivo.	J Am Dent Assoc 2011;142:4S-9S.	No final fracture load.
44	Skouridou N, Pollington S, Rosentritt M, Tsitrou E.[64]	Fracture strength of minimally prepared all-ceramic CEREC crowns after simulating 5 years of service.	Dent Mater 2013;29:e70-7.	No initial fracture load.
45	Slavcheva S, Krejci I, Bortolotto T.[65]	Luting of ceramic crowns with a self-adhesive cement: effect of contamination on marginal adaptation and fracture strength.	Med Oral Patol Oral Cir Bucal 2013;18:e799-803.	No initial fracture load.
46	Sundh A, Molin M, Sjögren G.[68]	Fracture resistance of yttrium oxide partially-stabilized zirconia all-ceramic bridges after veneering and mechanical fatigue testing.	Dent Mater. 2005 May;21(5):476-82.	No initial fracture load.
47	Tsalouchou E, Cattell MJ, Knowles JC, Pittayachawan P, McDonald A.[69]	Fatigue and fracture properties of yttria partially stabilized zirconia crown systems.	Dent Mater 2008;24:308-318.	No initial fracture load.
	Vult von	Fracture strength of two oxide	J Oral Rehabil	No initial fracture load.

48	Steyern P, Ebbesson S, Holmgren J, Haag P, Nilner K.[70]	ceramic crown systems after cyclic pre-loading and thermocycling.	2006;33:682-689.	
49	Zahran M, El-Mowafy O, Tam L, Watson PA, Finer Y.[71]	Fracture strength and fatigue resistance of all-ceramic molar crowns manufactured with CAD/CAM technology.	J Prosthodont 2008;17:370-377.	No final fracture load.
50	Zhao K, Wei YR, Pan Y, Zhang XP, Swain MV, Guess PC.[72]	Influence of veneer and cyclic loading on failure behavior of lithium disilicate glass-ceramic molar crowns.	Dent Mater 2014;30:164-171.	Monolithic restorations.

Supplement 1. Articles excluded after full-text screening and data analysis.